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WIRELESS CHANNEL MODELING BASED ON FINITE-STATE MARKOV MODEL

Florida Institute of Technology

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14. ABSTRACT
The main objective of the overall proposed research was to develop a robust video communication over Airborne Networks that are operation under time varying and error prone battlefield environments with limited bandwidth and potentially transmitting/receiving with mobile and portable devices. The overall robust video communication system aiming at providing high performance video transmission under dynamic and time varying Airborne Networks will be explained in the technology background section. The objective of the first phase of this project is to develop a channel simulation toolset that is able to capture some major characteristics of the Airborne Networks. The team at the Florida Institute of Technology has been able to implement a wireless channel simulation based on Finite-State Markov Model to simulate and analyze the error and loss characteristics. The simulation is currently based on command line execution.

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EXECUTIVE SUMMARY

The main objective of the overall proposed research is to develop a robust video communication over Airborne Networks that are operating under time varying and error prone battlefield environments with limited bandwidth and potentially transmitting/receiving with mobile and portable devices. The overall robust video communication system aiming at providing high performance video transmission under dynamic and time varying Airborne Networks will be explained in the technology background section. The objective of the first phase of this project is to develop a channel simulation toolset that is able to capture some major characteristics of the Airborne Networks.

During the first 12 months of this project period, the team at the Florida Institute of Technology has been able to implement a wireless channel simulation based on Finite-State Markov Model to simulate and analyze the error and loss characteristics. This is a crucial step towards the overall robust video transmission system to be developed specifically for Airborne Networks. By adopting the Finite-State Markov Model, we have also been able to obtain relatively accurate estimation of the channel parameters based on the training of the simulated channel loss with simplified Markov Model. The simulation is currently based on command line execution.

As this is only the first phase of the proposed overall system, the team is working on several next steps to refine the channel modeling with multi-stage Markov models and with more accurate estimation of channel parameters. The team is also working on the GUI (graphic user interface) for the simulation toolset for convenient user interface. This final report for the first year of the project summarizes the activities completed from January 2007 to December 2007.

1. Technology Background

1.1. Contemporary Enabling Technologies

Under today's Global Information Grid initiative, the Air Force is developing a contemporary Airborne Networking technology to meet the challenges of secure and reliable communication of battlefield critical information within the air-ground-space domains of military personnel and devices. Wireless networking, by its very own nature, is already facing significant problem due to time varying characteristics of the links and the constant moving of the receiving devices. However, Airborne Networking will face several additional challenges because of:

(1) Platform mobility is in the "mach" not "mph" in the ground networking scenarios
(2) Latency requirement is measured in "millisecond" not "second" in other applications
(3) Aircraft antennas usually have much less gains
(4) Increasing demand for video over airborne networks.

The requirement for significantly more video communication over Airborne Networks poses substantial challenges for the development of next generation Airborne Networks as many of the legacy airborne platforms are inherently running at low bit rate. The next generation Airborne Networks will need to ensure the smooth transitions from current legacy platforms to future robust networks.

Recent technological advances in the wireless communication and networking at the commercial front have enabled numerous applications based on mobile wireless networking. Currently, there are several commercially operational wireless networks enables seamless roaming of consumers across these wireless networks and offers unprecedented complexity of integrated services, ranging from voice, data, to graphics and video. In particular, significant research and development activities have been invested to develop applications for the streaming of multimedia data over wireless networks to a wide range of mobile portable devices.

On the other hand, the infrastructure development in wireless networks has been duly complemented by the tremendous advances in multimedia encoding technologies. In fact, the success of wireless multimedia, especially wireless video, in the consumer electronics sector, has been made possible by the successful development of a series of video coding standards: MPEG-1, MPEG-2, MPEG-4, H.263, and the most recent one H.264. The evolution of these video coding standards has spanned over several decades since the 1980's and has gone through several generations of development. Over the past two decades, these video coding standards allow high performance compression of video data so as to match with the limited bandwidth of wireless links for video transmission.

In addition to meeting the bandwidth compression requirements, recent video coding standards, such as MPEG-4 and H.264, also include a suite of error resilient tools in order to minimize the error impact from unreliable wireless links. Furthermore, to facilitate the heterogeneous wireless systems and mobile devices, both MPEG-4 and H.264 provide scalable coding profile so that the compressed video bitstream can be truncated at any bit rate to fit the heterogeneous bandwidth requirements of different wireless links and portable devices. It is the error resilient and scalable video coding strategy embedded in H.264 standard that matches well with the mission of video transmission task within the Air Force Airborne Networks.

In summary, the contemporary video coding standards are able to offer the following major benefits for robust video transmission over error prone Airborne Networks:

(1) Significant compression capability to meet the bandwidth constraints
(2) Error resilient capability to meet the error robust transmission requirement
(3) Scalable video profile to seamlessly meet the variable bandwidth of heterogeneous wireless links

1.2. From Commercial Technology to Airborne Networking Applications

It is true that the commercial wireless networks have achieved great success during the last decade, with deep penetration of cellular phones and mobile devices to hundreds millions of population worldwide. Much of the success is due to our full understanding of the wireless transmission media that enables the design of high performance networks and handheld devices such as cellular phones.

There is no doubt that the success of these commercial applications offers great lessons for developing video transmission system over Airborne Networks. However, major challenges remain in our attempt to extend the commercial applications to military battlefield scenarios. One of these significant challenges is that the wireless networks in Airborne Platforms are fundamentally different from the commercial ones, in their speed of mobility, latency requirement, antenna gains, and hostile environments. The lessons we learned in the development of commercial systems cannot be directly applied to the airborne networking applications because of these fundamental differences.

To develop a robust video communication system deployable in the Airborne Platforms, we need to first carefully investigate the characteristics of the wireless links within the Airborne Networking scenarios. Once we have the comprehensive knowledge of these unique wireless links, we can follow the successful strategies in the development of commercial wireless video systems to design, develop, and deploy the robust video communication systems in the Airborne Networking platforms.

It is clear that the first step to address the differences between commercial wireless links and the Airborne networking links will to develop mathematically tractable models for various Airborne Network links. It is with this consideration that we dedicate the first phase of the proposed robust video communication system to the modeling of such wireless links via the Finite-State Markov Model. We believe that such modeling will be able to offer some useful insight to design of the over video communication system for Airborne Networks.

In this report, we will first present the brief overview of the proposed robust video communication system. We will then focus on the report on the first phase of the proposed overall system, that is, the implementation of the Finite-State Markov Modeling of the wireless links and the proposed estimation of the wireless channels based on such modeling.

2. Robust Video Communications System Overview

The proposed robust video communications system will be designed, developed, and implemented by the collaboration between the research team at the Florida Institute of Technology and the researchers at Air Force Rome Research Lab. This system aims at providing high quality video transmission over severely impaired wireless links between nodes that are connected within the airborne networks. The target bit rate for the proposed video communication can be in the range between 24 Kbps and 384 Kbps with relatively high visual quality. However, we may allow the system to operate at extreme low bit rate down to 10 Kbps and at high bit rate up to 1.5 Mbps so that we are still able to push the video communication for some legacy communication networks and devices. To accommodate the large range of the data rate for heterogeneous wireless links and devices, we adopt the H.264 SVC standard for video coding and decoding. To overcome the adversity of the video transmission in tactical airborne wireless networks with various constraints in terms of bandwidth, channel impairments, both bursty errors and packet loss, and media access control for battery operated end users, we propose an end-to-end design principle that embrace the joint source and channel coding as the key strategy and the channel estimation and feedback as the means of providing adaptation. Various building blocks of the proposed system and the relationship between these building blocks are shown in Figure 1.

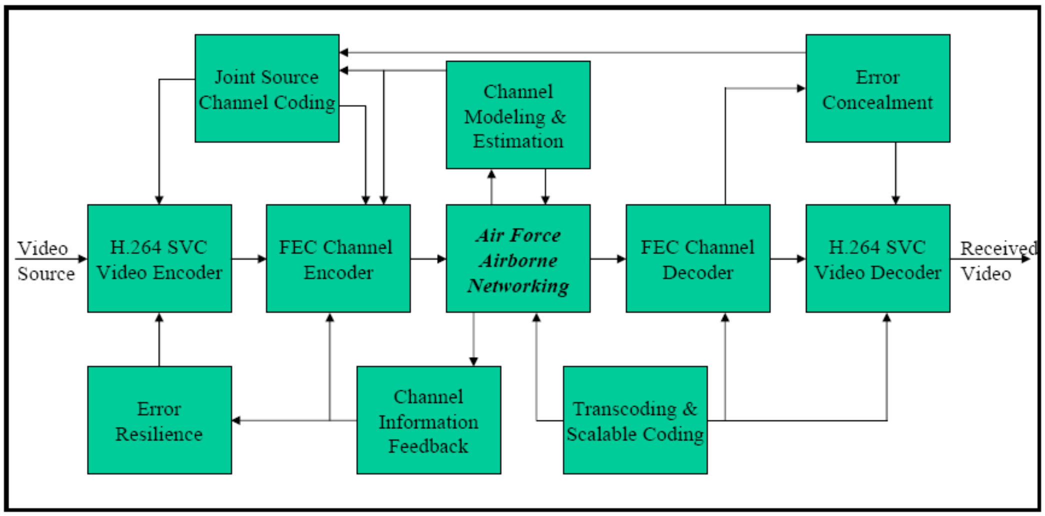


Figure 1: Building blocks for the proposed robust video communication system

In the following, we will present an overview of the proposed robust video communication system and will briefly introduce several major building blocks and their functionalities and relationships. Detailed description of all building blocks and design principles will be presented in the next Section.

Major Functionalities of the Proposed System

The proposed system can be divided into three major functionalities: (1) video source encoding and decoding, (2) error correction channel encoding and decoding, and (3) channel modeling and estimation. Since it has been well known that the joint source and channel coding is able to significantly improve the end-to-end quality of service for video transmission, these functional components can no longer be treated separately. This is evident form Figure 1 that many of these building blocks are interconnected to facilitate joint design of the end-to-end system. We describe in the following these three major functionalities and the strategies we take to implement these functionalities.

- **Video Encoding and Decoding:** We will employ H.264 SVC standard video coding as a base for video encoding and decoding. Such a selection of standard video codec will enable the smooth exchange of motion imagery among different DoD agencies as envisioned by the MISB. In addition to this important consideration, H.264 SVC video encoding and decoding schemes are inherently able to facilitate the required error control strategies, including error resilience tools, data partition for unequal error protection, and error concealment. Significantly improved results have been obtained by joint source and channel coding based on MPEG-4 codec for video delivery over both packet loss network and wireless fading channels. We will extend the previously developed MPEG-4 codec to H.264 SVC codec for this project.

- **Channel Encoding and Decoding:** The main reason for the incorporation of channel encoding and decoding is that the communication links between platform nodes within Airborne Networks can be severely impaired. The embedded error resilience in H.264 SVC video codec is inadequate to overcome such channel impairment. Additional error control strategies need to be implemented. We will carefully select a combination of error control codes for the proposed system because in order to combat the bursty error in the wireless links as well as the packet loss error due to networking management. In combination with intelligent interleaving, and the error resilient MPEG-4 tools, a joint design of channel coding and source coding has been shown to achieve high end-to-end quality of service for composite channel impairments with both packet loss and burst fading errors. We will extend this innovative approach to H.264 based joint source and channel coding schemes.
- **Channel Modeling, Estimation, and Feedback:** The design issues related to these functionalities will be crucial to the success of the end-to-end system design. The joint source and channel coding will rely on these functionalities to provide channel feedback information for an optimal allocation of bit budget for source coding and channel coding. Since the network links are changing constantly while there is latency between the channel feedback and algorithm adaptation, there is a need for the trade-off between accuracy and speed of the channel estimation. We will first investigate the fast estimation of partial channel information and develop the corresponding adaptation schemes, and then strive to estimation and feedback the complete channel information for joint source and channel coding adaptation. An additional functionality of the channel feedback is to decide whether or not the transcoding or scalable coding needs to be activated in order to reach certain edge users or edge devices that have considerably different bandwidth than the majority of the platforms within Airborne Networks.

In summary, these major functionalities cover all the building blocks within the proposed video communications system. Several building blocks serve across functionality boundaries and operate as platforms for joint design. One example is the JSCC block that serves across source coding and channel coding boundaries. The JSCC also interact intimately with the channel modeling, estimation, and feedback blocks that bridge between the transmitting ends with receiving ends.

3. Technical Rationales for Finite-State Markov Modeling

The ultimate goal in robust video communication system design is to control and optimize the end-to-end performance adaptively according to the instantaneous channel conditions of the communication links. In the civil and commercial wireless communication applications, extensive studies on the channel and networking characteristics have been carried out and the design of communication systems can be optimized based on the instantaneous feedback of the channel information or the statistical behavior of the channel characteristics. To develop a robust video communication system for airborne networks, the first task will be to model and simulate the channel characteristics of these dynamic, ad hoc, and often hostile wireless links. Once we have collected adequate information on the channel characteristics of these links, we shall be able to apply the joint source and channel coding principles that have been successfully employed in commercial applications to the Air Force Airborne Networks.

There are several key technologies that are required in order to successfully develop the proposed robust video communication systems. We will first focus on the channel modeling and simulation in order to provide the basic information for the subsequent adaptive joint source and channel coding schemes. We will then outline the strategy for channel bandwidth or data rate regulation to achieve the desired adaptation to optimize the video transmission performance. Such adaptation is based on the well-known H.264 SVC standard as well as the possible punctured channel coding techniques.

In this report, we will focus on the channel modeling and simulation based on Finite-State Markov Modeling. Once the tools for such modeling are developed, a systematic investigation of the modeling and simulation can be carried out and the results will be useful for the design and development to proposed robust video communication systems.

1.3. Wireless Channel Modeling Using Finite-State Markov Model

In the project, the first order Finite-state Markov Model (FSMM) has been employed to characterize the error and loss behavior of dynamic wireless network and its implementation. In the following, the FSMM principles will be outlined and the procedure to train and estimate the wireless links will also be presented

3.3.1. Finite-sate Markov Model (FSMM)

A finite-state Markov model is defined as a finite set of states $S = \{s_0, s_1, \cdots, s_{K-1}\}$, where K is the number of states. A binary symmetric channel (BSC) with a given crossover probability is associated with each state $s_k, k \in \{0,1,2,\cdots\}$, so the channel quality for each state can be identified. Let $\{S_n \mid S_n \in S, n = 0,1,2,\cdots\}$ to be a constant Markov process. Since the constant Markov process has the property of stationary transitions, the transition probability is independent of time index n, so

$$t_{j,k} = \Pr\{S_{n+1} = s_k \mid s_n = s_j\} \quad k, j \in 0,1,2,\cdots K-1 \qquad (1)$$

is a constant $K \times K$ matrix, which is called the state transition probability matrix T. The state transition probability matrix is an important parameter for a finite-state Markov model. Note that the sum of the elements on each row of T is equal to 1.

$$\sum_{l=0}^{K-1} t_{kl} = 1, \forall k \in \{0,1,2,\cdots\} \qquad (2)$$

Another parameter for a finite-state Markov model is the crossover probabilities in each state, $e_k, k \in \{0,1,2,\cdots\}$.

The last parameter for a finite-state Markov model is the steady state probability of each state, $p_k, k \in \{0,1,2,\cdots\}$. But the steady state probabilities are not independent. The steady state probability p_k for state s_k can be viewed as the probability of from all states transition to state s_k, so

$$\sum_{j=0}^{K-1} p_j t_{j,k} = p_k, \forall k \in \{0,1,2,\cdots, K-1\} \qquad (3)$$

The functions only have zero solution. But $\sum_{k=0}^{K-1} p_k = 1$ (4)

With any $K-1$ functions from (3) and the function (4), the $p_k, k \in \{0,1,2,\cdots\}$ can be determined with any given state transition probability matrix T.

3.3.2. Training A Finite-state Markov Model

To use the finite-state Markov model to model a dynamic wireless communication channel, one should decide the parameters of a finite-state Markov model. We call the process of using a series of known data to estimate the parameters of a finite-state Markov mode training a finite-state Markov model.

After determine the parameters of a finite-state Markov mode, one generate a series of states, which hopefully can model the characteristics of the modeled wireless channel.

1.4. Implementation of Finite-State Markov Model

We use C++ implement the any number of states finite-state Markov model, which is defined as class as following:

```
class FSMC
{
public:
	FSMC(int num = 2);  //construction function, with num as the number of states, default is 2.
	~FSMC();
	void set_tran_matrix(double *matrix);   //set the transition matrix
	void set_state_prob(double *s_p);      //set the steady state probabilities
	void set_pe(double *p_e);            //set the crossover probabilities
	char oneStep();                 //generate the next state
	void fsm_train(char *data,int train_len); //use data to train a finite-state Markov model
	void show();                    //show the Markov model

private:
	int num_state;                  //number of states
	int current_state;              //current state
	double **tran_matrix;           // transition matrix
	double *state_prob;             // steady state probabilities
	double *pe;                     // crossover probabilities
};
```

Since we don't have data right now, so we use a known finite-state Markov model to generate a series artificial data and use those data to train a new finite-state Markov model. The trained model should have the same parameters with the given finite-state Markov model.

The software right now is the command line form, which takes an input of a finite-state Markov model, to train a now finite-state Markov model, show and compare the given and trained models.

How to use:
Since the transition matrix can determine the steady state probabilities, so we only need input, so we only need to input the transition matrix for the given model. The software takes input in two ways:

1. The program read the transfer matrix from a file (for example "data.txt"):
input "fsm data.txt" in command line

2. input the elements of transfer matrix from command line one by one:
input "fsm" in command line

For example, we have following data in file "data.txt" (we assume the state can only transfer to itself or adjacent states)

```
4
0.04  0.96  0     0
0.04  0.92  0.04  0
0     0.06  0.92  0.02
0     0     0.05  0.95
```

The number in the first line is the number of states, followed by the state transition matrix. If we input "fsm data.txt " in command line, we can get the following results:

```
The original Finite State Markov Chain:
Transfer Matrix:
    0.04        0.96         0          0
```

0.04	*0.92*	*0.04*	*0*
0	*0.06*	*0.92*	*0.02*
0	*0*	*0.05*	*0.95*

Steady State probability:

0.0210971 0.506329 0.337553 0.135021

The Trained Finite State Markov Chain:

Transfer Matrix:

0.0423045	*0.957696*	*0*	*0*
0.0407675	*0.919227*	*0.0400053*	*0*
0	*0.0597448*	*0.920473*	*0.0197793*
0	*0*	*0.0504601*	*0.94954*

Steady State probability:

0.021558 0.506433 0.339092 0.132917

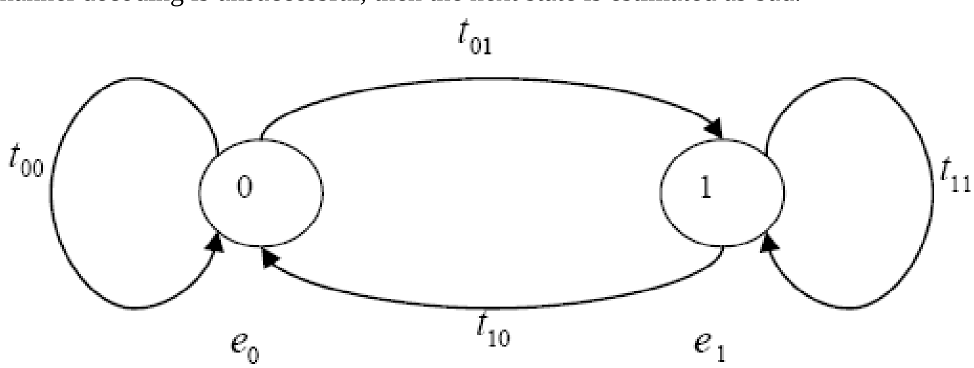
We can see from the results that the trained model almost have the same parameters with the given model.

1.5. Channel Estimation Using FSMM

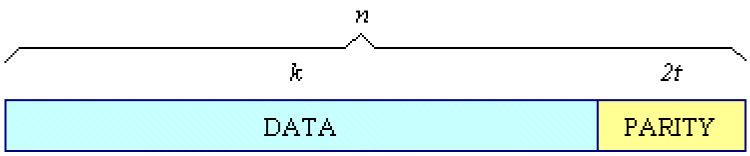
We propose the following channel state estimation at the decoder. The decoder estimates the channel state for the next one or several transmissions (according to application latency) based on the current received packet and the packet after channel decoding. Each video packet is protected by different strong level of FEC, depending on the important of video coding layer and the current channel state. After receiving one packet, the decoder first does channel decoding.

Based on the received original packet and the packet after channel decoding, the channel estimation method is outlined as following:

- If the channel decoding is successful, we can compare the received original packet and the packet we get after decoding. The different number of bits should be the number of transmission error. The number of transmission error divided by the length of the packet, is the error probability p_e .
- If current state is good, then the next state is estimated as good;
  Else if current state is bad:
  If $p_e < e_0$ (the crossover probabilities of good state), then the next state is estimated as good;
  Else, the next state is estimated as bad.
- If channel decoding is unsuccessful, then the next state is estimated as bad.



Currently, the channel state estimation only supports2 states case. The simulation is based on Reed-Solomon code as following:



n=255, t = NUM_ERR_GOOD/ NUM_ERR_BAD
NUM_ERR_GOOD and NUM_ERR_BAD are two macros defined in fsmApp.cpp, which stands for number of bit error per frame in good channel state and bad channel state respectively.

1.6. Summary and Discussion

In summary, this report outlines the modeling and simulation of wireless channels in order to characterize the dynamics of the Airborne Networks links. Initial investigations show that the proposed modeling based on finite-state Markov model is able to capture some key features of the channel with transient probability for state transitions. If the funding for the second year and beyond is continued, the team will continue the investigation and hope to capture more key features of the wireless links in Airborne Networking.

The next steps of investigation may include the following:

- ❑ Expand the initial model to include more states within the FSMM so that more transient characteristics can be capture
- ❑ Investigate more robust estimation algorithms so the estimation of channel conditions can be more accurate and faster
- ❑ Work on the implementation of graphics user interface by working with Air Force Rome Lab technical contact so that the simulation can be more user-friendly.

4. Software Packages

The software package generated out of this research project will be included in a separate CD which will be sent to AFRL for deposit. In addition to the software package for Finite-State Markov Modeling, this team has also modified the H.264 Scalable Video Coding (SVC) software used to integrate the proposed robust video communication system. This SVC software package is also included in the submission.

5. Acknowledgement

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6. Appendix

The investigation of the first phase of this project has been reported formally at SPIE Conference on Multimedia Systems and Applications X, ***Proc. of SPIE*** edited by Susanto Rahardja, JongWon Kim, Jiebo Luo, Vol. 6777, pages 677702-1 – 677702-8.

H.264 Scalable Video over Finite-State Markov Chain Wireless Channels*

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ABSTRACT

In this paper, a wireless channel is viewed as a heterogeneous network in the time domain, and an adaptive video transmission scheme for H.264 scalable video over wireless channels modeled as a finite-state Markov chain processes is presented. In order to investigate the robustness of adaptive video transmission for H.264 scalable video over wireless channels, statistical channel models can be employed to characterize the error and loss behavior of the video transmission. Among various statistical channel models, a finite-state Markov model has been considered as suitable for both wireless links as Rayleigh fading channels and wireless local area networks as a combination of bit errors and packet losses. The H.264 scalable video coding enables the rate adaptive source coding and the feedback of channel parameters facilitates the adaptive channel coding based on the dynamics of the channel behavior. As a result, we are able to develop a true adaptive joint source and channel based on instantaneous channel estimation feedback. Preliminary experimental results demonstrate that the estimation of the finite-state Markov channel can be quite accurate and the adaptive video transmission based on channel estimation is able to perform significantly better than the simple channel model in which only average bit error rate is used for joint source and channel coding design.

Keywords: H.264, Scalable video coding, finite-state Markov chain, channel state estimation, unequal error protection

1. INTRODUCTION

The demand for high-quality mobile wireless communication services (multimedia broadcasting, video streaming, video telephony, etc) beyond conventional voice communication is increasing at an explosive rate. However, the time-varying characteristics of wireless channel still remain a significant obstacle for reliable wireless communication. From the link layer point of view, the time-varying characteristic of the wireless channel is its dynamic bit error and packet over time. From application layer point of view, its bandwidth is dynamic with time, so wireless channel can be viewed as a heterogeneous network in time domain. Scalable video, designed for heterogeneous networks, can be used with a wireless channel to adapt the time variance in bit error and packet loss.

The scalable extension of H.264/MPEG4-AVC is a current standardization project of the Joint Video Team (JVT) of the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG). This amendment to the H.264 standard is expected to be finalized at the 24th JVT meeting 29 June 2007. Most components of H.264/MPEG4-AVC are used as specified in the standard. The base layer of an SVC bit-stream is generally coded in compliance with H.264/MPEG4-AVC, and each standard conforming H.264/MPEG-4 AVC decoder is capable of decoding this base layer representation when it is provided with an SVC bit-stream. The experimental results show that coding efficiency of H.264 scalable video coding is much better than previous scalable video coding (such as MPEG-4 FGS). For SNR scalability, the performance of H.264 scalable video coding is very close to that of single layer coding [1].

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In this paper, we investigate the new H.264 scalable video coding on an error prone wireless channel. As we all know, due to multi-path, mobility, terrain and a lot of other complicated reasons, the wireless channel are unreliable and dynamic. In order to investigate the performance of adaptive video transmission for H.264 scalable video over the wireless channels, we model the channel as a finite-state Markov model. Finite-state Markov modeling of a communication channel is a simple and effective approach for communication channel description [2]. To transmit scalable video over heterogeneous networks, the encoder must know the capacity of each link in order to deliver a suitable video stream (suitable base layer and enhancement layer descriptions) to each link. This video stream can make sure the decoder at each link can get the best quality of video under the given link capacity. When applied to the wireless channel, i.e., the time domain heterogeneous network, the encoder should know the channel state at the each transmission time. If the channel is good, the encoder can generate a better description and use lighter FEC protection; if the channel is not so good, the encoder can generate a suitable description and use stronger FEC protection. So channel estimation is a very important task in delivering H.264 scalable video coding over the wireless channel. We propose a channel estimation method based on the decoding process in the decoder, and feed back the channel state to the encoder to help the encoder to deliver best quality video based on the estimated channel condition.

The rest of this paper is organized as follows: In Section 2, an overall system description of the proposed scheme is given. We will also discuss both scalable H.264/AVC codec and channel state estimation based on finite-state Markov Chain. In Section 3, experimental results are reported to demonstrate that the proposed scheme indeed is able to perform significantly better than the non-rate adaptive system. Section 4 concludes this paper with summary and discussion.

2. SYSTEM DESCRIPTION

The proposed scalable video transmission over a time-varying wireless system is shown in Figure 1. At the encoder side, base and enhancement layers are generated by scalable extension of H.264/AVC [3]. With the feedback of estimated channel state information, channel codes are adaptively assigned, check sum bits are added, and the bit stream of enhancement layer is controlled in order to meet the available bandwidth. At the receiver side, the transmitted corrupted signals might be corrected by channel decoding and residual errors are detected by check sum bits. Then, channel state will be estimated using finite-state Markov chain. For video reconstruction, corrupted packets are dropped and finally transmitted video sequences are reconstructed using error concealment.

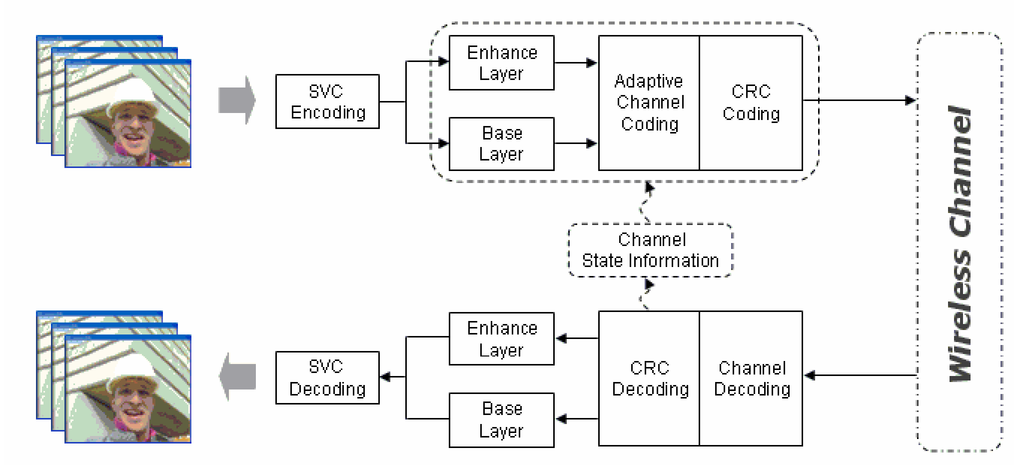

Figure 1: The proposed MIMO system

2.1 Scalable Extension of H.264/AVC

With the proposed video transmission scheme over the wireless heterogeneous networks, multi-layered video bit streams are essential and thus created by SVC [3] in this research. In this sub-section, we briefly review this video codec which is an extension of the H.264/AVC [5][6] video coding standard. Traditionally, there are two different ways for scalable video codec: either by using a technique that is intrinsically scalable (such as bit-plane arithmetic coding) or by using a layered approach. SVC supports a combination of the two approaches so that a full spatio-temporal and quality scalable codec is achieved. A coded SVC video sequence consists of a series of Network Abstraction Layer (NAL) units, each containing the layer information. A 4-byte SVC NAL unit header, an extension of H.264/AVC NAL, indicates the decoding dependency relationship of spatial, temporal, and quality scalability.

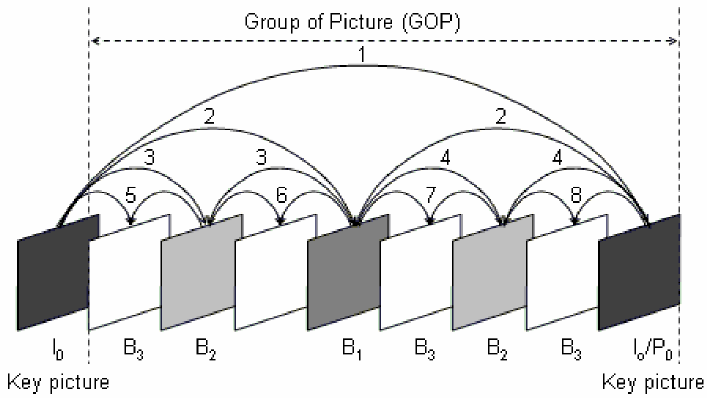

Figure 2: an example of temporal decomposition

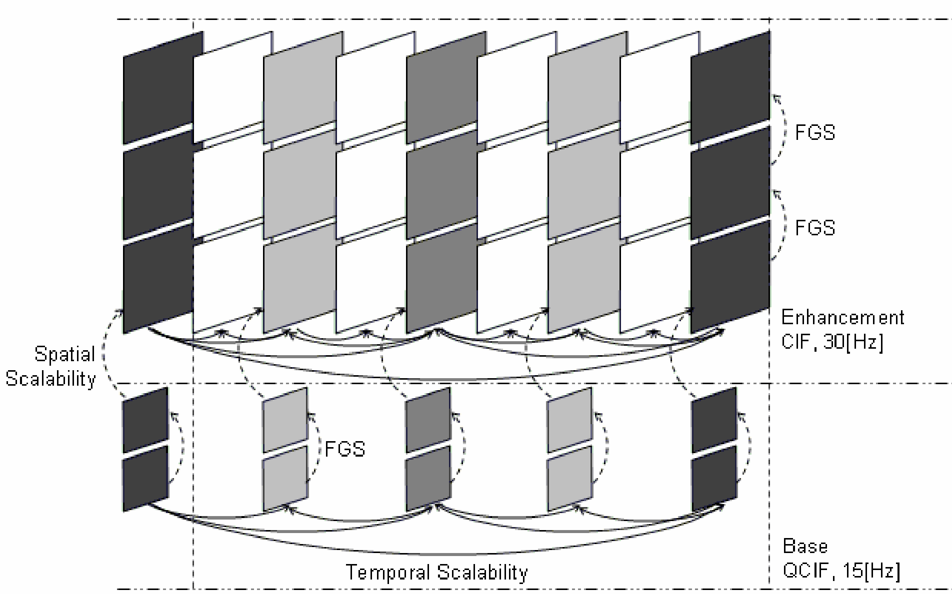

Figure 3: an example of combined scalability

The temporal scalability of SVC is typically given based on the principle of hierarchical B pictures. A hierarchical prediction structure with 4 dyadic hierarchy stages (or 4 temporal scalability levels) is described in Figure 2. In a video sequence, the first picture (key picture) is intra-coded as IDR picture and next key picture will be either intra-coded or inter-coded using previous key picture. All pictures between two key pictures are hierarchically predicted and encoded. Therefore, a group of picture (GOP) is created by a key picture and all pictures that are temporally located between a key picture and the previous key picture. Spatial scalability is also supported based on existing multi-layered coding approach. As depicted in Figure 3, the difference of spatial resolution between base layer and enhancement makes it achieve spatial scalability.

For quality (or SNR) scalability, SVC supports two types: coarse grain scalability (CGS) using various inter-layer prediction techniques and fine grain scalability (FGS) known as progressive refinement. In this work, we adopt FGS for SNR scalability in order to both satisfy each layer's target bit-rate and increase the error robustness. Within each spatial resolution FGS is achieved by encoding successive refinements of the transform coefficients. Therefore, a picture is represented by base representation and FGS refinement representations by repeatedly decreasing the quantization step size. The NAL units of FGS refinement layers can be truncated at any arbitrary point at the encoder and thus error robustness is increased by the decoder capable of arbitrarily discarding corrupted NAL unit streams. An example of combined scalability with group of picture (GOP) 8 is applied in experiments and described in Figure 3. For a more detailed explanation on SVC, see [3][4].

2.2 Finite State Markov Chain

A finite-state Markov model is defined as a finite set of states $\boldsymbol{S} = \{s_0, s_1, \cdots, s_{K-1}\}$, where $\boldsymbol{K}$ is the number of states (Figure 4 shows an example of 2-state Markov model). A binary symmetric channel (BSC) with a given crossover probability is associated with each state $s_k, k \in \{0,1,2,\cdots\}$, so the channel quality for each state can be identified. Let $\{S_n \mid S_n \in S, n = 0,1,2,\cdots\}$ be a constant Markov process. Since the constant Markov process has the property of stationary transitions, the transition probability is independent of time index n, so

$$t_{j,k} = \Pr\{S_{n+1} = s_k \mid s_n = s_j\} \quad k, j \in 0,1,2,\cdots K-1 \tag{1}$$

is a constant $K \times K$ matrix, which is called the state transition probability matrix $\boldsymbol{T}$. The state transition probability matrix is an important parameter for a finite-state Markov model. Note that the sum of the elements on each row of $\boldsymbol{T}$ is equal to 1.

$$\sum_{l=0}^{K-1} t_{kl} = 1, \forall k \in \{0,1,2,\cdots\} \tag{2}$$

Another set of parameters for a finite-state Markov model are the crossover probabilities in each state, $e_k, k \in \{0,1,2,\cdots\}$ .The last parameter for a finite-state Markov model is the steady state probability of each state, $p_k, k \in \{0,1,2,\cdots\}$. But the steady state probabilities are not independent. The steady state probability p_k for state s_k can be viewed as the probability of all states transitioning to state s_k, so

$$\sum_{j=0}^{K-1} p_j t_{j,k} = p_k, \forall k \in \{0,1,2,\cdots,K-1\} \tag{3}$$

The functions only have zero solution. But $\sum_{k=0}^{K-1} p_k = 1$ (4)

With any $K-1$ functions from (Eq. 3) and the function (Eq. 4), the $p_k, k \in \{0,1,2,\cdots\}$ can be determined with any given state transition probability matrix $\boldsymbol{T}$.

So the K-state Markov model is decided by its parameters: state transition probability matrix $T = [t_{jk}], j,k \in [0,1,...K-1]$ and crossover probabilities $e_k, k \in [0,1,...,K-1]$. These states and its crossover probabilities determine the channel quality for any wireless links modeled by such a Markov model. When an estimation of the channel model can be obtained, an adaptive video transmission scheme can be designed to take full advantage of the known channel parameter and the dynamics of the channel behavior. The parameters of the finite-state Markov channel model can be obtained by collecting traces under various network conditions.

2.3 Channel State Estimation

We propose the following channel state estimation at the decoder. The decoder estimates the channel state for the next one or several transmissions (according to application latency) based on the current received packet and the packet after channel decoding. Each video packet is protected by different strong level of FEC, depending on the important of video coding layer and the current channel state. After receiving one packet, the decoder first does channel decoding.

Based on the received original packet and the packet after channel decoding, the channel estimation method is as following:

If the channel decoding is successful, we can compare the received original packet and the packet we get after decoding. The different number of bits should be the number of transmission error. The number of transmission error divided by the length of the packet, is the error probability p_e.

If current state is good, then the next state is estimated as good;

Else if current state is bad:

If $p_e < e_0$ (the crossover probabilities of good state), then the next state is estimated as good;

Else, the next state is estimated as bad.

If channel decoding is unsuccessful, then the next state is estimated as bad.

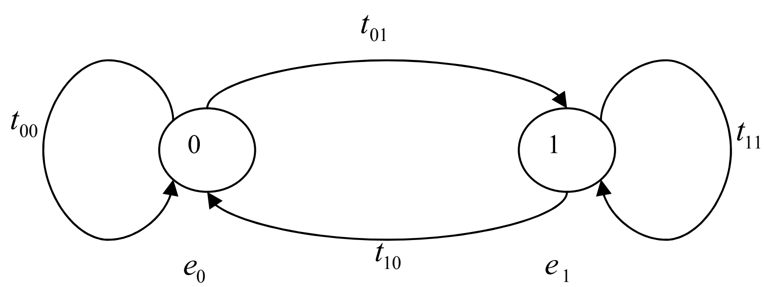

Figure 4: A two-state Markov chain model

2.4 Video Reconstruction

If the bit errors are above the capacity of the assigned channel coding, the transmitted packets might be corrupted and are dropped before video reconstruction. Then, error concealment is processed at the decoder. The detection of one or more missing pictures is done by calculating the frame number gap, picture order count (POC) gap, and the GOP size. If a base layer packet is lost, the corresponding enhancement layer packet is invalid and will be regarded as a lost packet also. We adopt picture copy (PC) algorithm in this work. With this error concealment, each sample of value of the concealed picture is copied from the corresponding sample of the first picture in the reference list 0. The base layer PC will only be done when decoding a low resolution sequence. A lost enhancement layer picture will be concealed using the first picture in the reference picture list 0. The list 0 is generated from the decoding process of the enhancement layer and it contains only high resolution pictures.

3. EXPERIMENT RESULTS

We provide numerical examples to show how the proposed video transmission scheme with adaptive channel coding is able to achieve stable reconstructed video over time-varying wireless channel.

3.1 Performance of Channel State Estimation

Using the proposed method above, we conduct the prediction experiments based on different Markov models. We tested different state transition matrix. In all cases, the crossover probabilities of the good state is 0.1%; and the crossover probabilities of the bad state is 10%. Table 1 gives the prediction error with different Markov models. From the table we can see that when the transition probabilities between the states become larger, the prediction error also becomes larger. This is because when the transition probabilities between the states are large, the channel becomes "unstable", it is not easy to predict the next state based on previous states.

Table 1. Prediction errors with different Markov models

State transition matrix	Prediction Error (%)
$\begin{bmatrix} 0.99875 & 0.00125 \\ 0.005 & 0.995 \end{bmatrix}$	0.202
$\begin{bmatrix} 0.99 & 0.01 \\ 0.02 & 0.98 \end{bmatrix}$	1.35
$\begin{bmatrix} 0.98 & 0.025 \\ 0.025 & 0.97 \end{bmatrix}$	2.48

3.2 Performance of Reconstructed Video PSNR

In this sub-section, we conduct experiments to show the performance of the proposed system with reconstructed PSNR of the decoded video sequences. As shown in sub-section 3.1, the prediction of channel state (CS) estimation would be quite accurate if the transition probabilities between the states become large. Thus, in this sub-section, we conduct an experiment with ideal case that the channel state estimation is perfect and no delay. Three video sequences, 'Mobile', 'Carphone', and 'Foreman', are tested. All test sequences are 64 frames with CIF 15[Hz] and encoded by scalable H.264/AVC reference model JSVM 7.0 [4] to generate 2-layer scalable video bit-streams with GOP size 8. Reed-Solomon (RS) Codes [7] are adopted to protect the transmitted bit-streams since it maintains maximum erasure protection while produces a minimum of redundancy. We assume that 640 [Kbits/sec] is available as data rate and then 256[Kbits/sec] is assigned for base layer and 384[Kbits/sec] is utilized for enhancement layer. Then, in order to achieve unequal error protection (UEP), different channel coding redundancies are assigned for base and enhancement layers. Fixed UEP RS codes are assigned in no CS feedback system while assigning adaptive UEP RS codes in the proposed system that has the feedback of CS. Note that the enhancement layer bit streams are adaptively dropped to adjust the RS channel coding according to the channel state so as to achieve the adaptive transmission scheme with the fixed available data rate

The average reconstructed PSNR (luminance component) for 'Mobile', 'Foreman', and 'Carphone' are shown in Figure 5, Figure 6, and Figure 7, respectively. In these figures, we clearly demonstrate that the proposed adaptive transmission scheme (with CS Feedback) based on channel state estimation achieves steady reconstructed video sequences over time-varying wireless networks as compared with non-rate adaptive source coding system (w/o CS Feedback). In table 2, we illustrated the average reconstructed PSNR of three test sequences.

Table 2. Average reconstructed PSNR of test sequences

	Mobile	Carphone	Foreman
w/o CS Feedback	26.13 [dB]	33.76 [dB]	28.35 [dB]
with CS feedback	32.53 [dB]	37.42 [dB]	35.82 [dB]

4. CONCLUSION

We propose in this research an adaptive video transmission based on H.264 scalable video coding and the adaptive channel estimation based on finite-state Markov model (See Figure 4). The H.264 scalable video coding enables the rate adaptive source coding and the feedback of channel parameters facilitates the adaptive channel coding based on the dynamics of the channel behavior. As a result, we are able to develop a true adaptive joint source and channel based on instantaneous channel estimation feedback. Preliminary experimental results demonstrate that the estimation of the finite-state Markov channel can be quite accurate and the adaptive video transmission based on channel estimation is able to perform significantly better than the simple channel model in which only average bit error rate is used for joint source and channel coding design. The proposed methods can be easily extended to multi-state Markov model based on different application scenarios.

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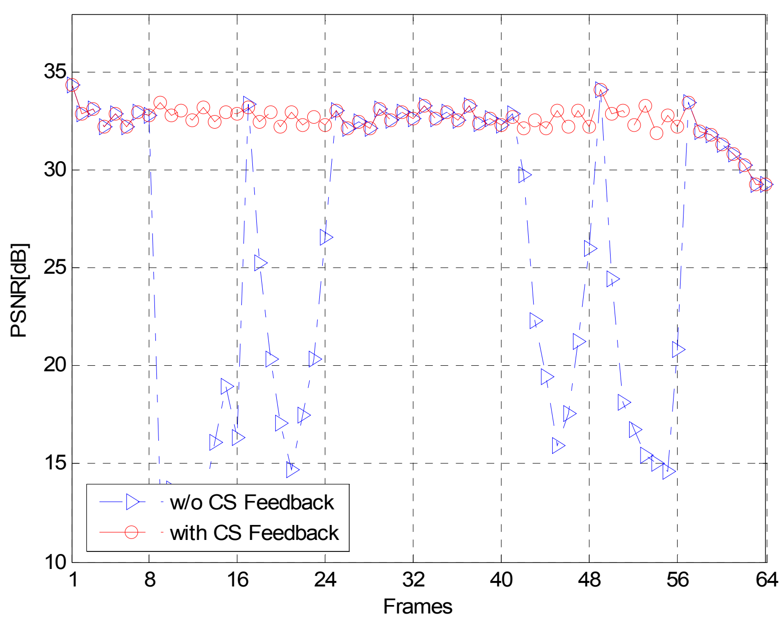

Figure 5: Reconstructed PSNR of Mobile

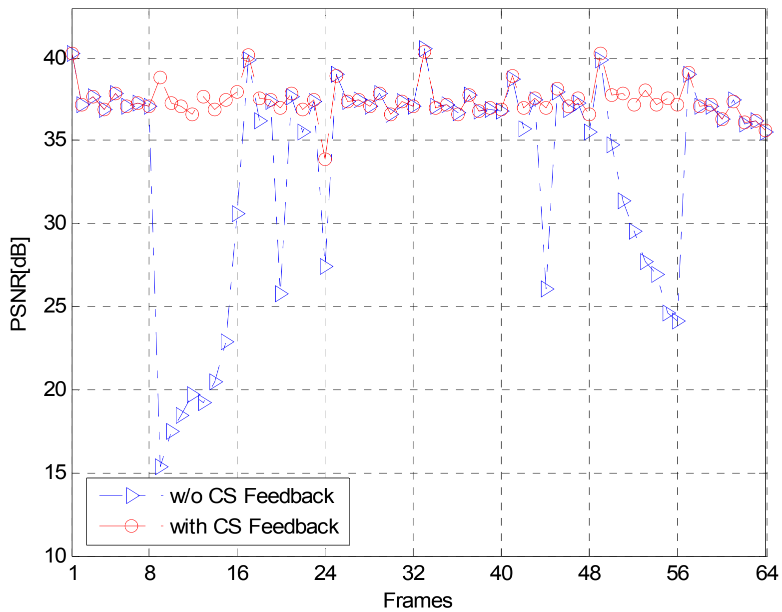

Figure 6: Reconstructed PSNR of Carphone

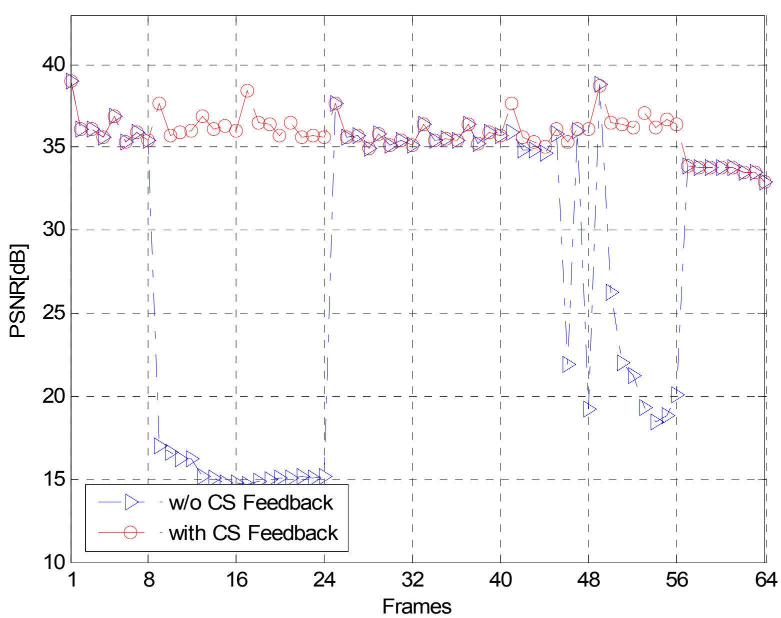

Figure 7: Reconstructed PSNR of Foreman